Towards A Coupled Environmental Prediction System

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Abstract

Two high resolution modeling efforts are presented towards the goal of developing a coupled environmental prediction system. A 0.1^{o}, 40-level North Atlantic configuration of the Los Alamos National Laboratory Parallel Ocean Program (POP) model, forced with 1993-1997 Navy Operational Global Atmospheric Prediction System (NOGAPS) wind stresses, is used to address the feasibility of using POP in a future Navy global air/ocean/ice prediction system. A 1/12^{o} and 45-level, coupled ocean/ice model of the Pan-Arctic region that uses POP and a viscous-plastic ice formulation, has been developed to provide the U.S. Navy with a next generation operational model to predict sea ice and upper ocean conditions in the northern hemisphere The Arctic model domain extends from ~30^{o}N in the North Pacific, through the Bering Sea, Arctic Ocean and Nordic Seas to ~40^{o}N in the North Atlantic. Basin/regional models are used for proof of concept and computational efficiency. Quantitative model evaluations using data that capture features and high-frequency ocean processes of importance to operational needs are used to assess model performance. The ability of the models to reproduce short-term climate variability is also addressed. To demonstrate the need for high resolution some of the evaluations are repeated using coarser resolution runs.

Lagrangian and Eulerian statistics are calculated from North Atlantic World Ocean Circulation Experiment (WOCE) surface drifters, a coarser resolution POP run (0.28^{o}, 20-levels), and the 0.1^{o} North Atlantic simulation. The Eulerian comparisons show that the mean and variability of the higher resolution surface circulation are very realistic, while in the coarser run, features are inaccurate in places and energy levels are significantly under-represented. Similarly, details of the Arctic Ocean and ice circulation will be compared with a coarser resolution run. Other North Atlantic evaluations include the position of the Gulf Stream north wall, and mixed layer depths. Details of a new 0.1^{o}, 40-level global configuration of POP are presented.

Introduction

The vision for Navy meteorological and oceanographic prediction in the next decade is that of a high resolution global coupled air/ocean/ice model that assimilates data, providing initial conditions from which a forecast is performed. Additionally, very-high resolution regional air/ocean coupled models will be nested into the global system at key locations. We are making progress towards this goal on several fronts: the development of a new state-of-the-art coupled ice/ocean model for predictive use in the Pan-Arctic and the testing of a general circulation ocean model to assess its potential use in the future forecasting system.

The ocean model under consideration for potential use in both the global and regional prediction systems is the LANL POP model. It is a primitive, equation, z-level model that runs on most multi-processor machines. Bench-marking shows the code to be highly scalable onto a large number of processors (Semtner, 2000).

One of the goals of our challenge project is to run a global configuration of POP that adequately reproduces features and processes important to Navy prediction. In our original proposal, we had stated that it was likely that 0.1 ^{o} horizontal resolution and 40 vertical levels would be required to achieve this goal, but the resources required for such a run were prohibitive at that time. Instead we proposed a 1/6 ^{o}, 40-level global configuration. In the meantime, to resolve this issue, we began a 0.1 ^{o}, 40-level basin-only (North Atlantic) POP run that could be compared with appropriate data and the results from an earlier 0.28 ^{o}, 20-level POP simulation conducted several years ago at LANL. This simulation was started prior to the beginning of the challenge project however there were insufficient resources to make headway until we obtained challenge status. Obtaining quantitative measures of the model's performance at very-high resolution was necessary before committing to a resolution, so we opted to first complete the North Atlantic run.

The main goal of the Polar Ice Prediction System (PIPS) 3.0 project is to deliver a new state-of-the-art coupled ice-ocean model to significantly improve the U.S. Navy operational forecasts of sea ice and ocean conditions in the northern high latitudes. This new model in its final phase will be transitioned into an operational setting at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, California. Model forecasts will be routinely analyzed at the National and Naval Ice Center in Washington D.C. and distributed to the on-scene commanders to improve skill and safety of naval operations, especially those involving the submarine fleet and undersea warfare systems. It is important to note here that one of the critical requirements for a successful completion of this project is its full utilization of computational resources available to DOD users through the HPCMP program.

Towards a high-resolution global ocean POP simulation:

The 0.1 ^{o}, 40-level North Atlantic POP simulation was initialized from an earlier 15-year run with the same resolution (Smith et al., 2000). Our simulation was forced with five years (1993-1997) of daily Navy Operational Global Atmospheric Prediction System (NOGAPS) winds and Barnier et al. (1995) climatological heat fluxes. A mixed layer (Large et al., 1994) was active. It was not possible to use the Smith et al. (2000) run as it was not forced with Navy winds, it had no mixed layer, and most importantly, output was not saved sufficiently often to study the high-frequency processes important to Navy prediction. The domain extends from roughly 20 ^{o} S to 72 ^{o} N and from 98 ^{o} W to 17 ^{o} E. For computational efficiency, the Gulf of Mexico west of 82 ^{o} W was wrapped around into array addresses occupied by the African land mass. A snapshot of upper-level temperature (5 m) is shown to demonstrate the richness of the simulated eddy field and frontal structures (Figure 1). The 0.28 ^{o}, 20-level POP run is near-global extending from 20 ^{o} S to 70 ^{o} N

(Maltrud et al., 1998).

To assess the ability of POP to reproduce features and processes important to Navy prediction, statistical quantities from the model and high-frequency data in the North Atlantic are compared. In particular, the mean and variability of the surface circulation, and the upper ocean thermohaline structure are considered. The recent World Ocean Circulation Experiment (WOCE) that spanned much of the past decade, provided the high quality data used in these evaluations. The spatial and temporal coverage by the WOCE surface drifters in this basin is extensive (Figure 2), providing an excellent data base from which to calculate statistics of the surface circulation. The Joint Environmental Data Analysis (JEDA) Center at Scripps Institute of Oceanography, using an optimal interpolation scheme, provides a monthly realization of the global mixed layer depth (MLD) derived from Expendable Bathythermographs (XBTs). In this case, the MLD is the depth over which the upper water column temperature is homogeneous.

To obtain measures of the fidelity of the model surface circulation, Eulerian statistics were calculated from two years (1993-1994) of WOCE surface drifter velocities and co-located model velocities from the two model runs. These comparisons show the mean and variability of the surface circulation in the higher resolution run to be very realistic relative to the drifter fields while in the coarser run, features are inaccurate in places and energy levels are significantly under-represented. The velocity variability is shown here in terms of principal standard deviation ellipses for the data, the 0.1^{o} and the 0.28^{o} runs (Figures 3a, b, and c). Note the significant increase in variability across the domain in the higher resolution case. Particularly noticeable is the increased reproduction of the variability in the vicinity of the Azores Front (around 35^{o} N) offshore from the Mediterranean Sea, and in the Gulf Stream. The variability associated with the sharp northward turn of the North Atlantic Current known as the Northwest Corner, which occurs just past the Grand Banks in the real ocean, is inaccurately reproduced in the mid-basin in the coarser resolution case. These statistics clearly indicate that using an ocean model with a horizontal resolution of roughly $1/6^{o}$ will be inadequate in the future global prediction system. This fact is further supported by Lagrangian, or trajectory-based, statistics calculated from the 0.28^{o} run and the data. The numerical trajectories are calculated using a 4th-order Runge-Kutta scheme from the model velocity fields (Figure 4). The coverage of the domain is not as uniform as in the case of the data and notable ``holes'' are to be seen. Length and time scales are then calculated from the two sets of trajectories. These scales which represent the distance and time over which the particle remembers its path, and are too short and long, respectively.

Monthly averages of the mixed layer depths from the 0.1^{o} model are binned into the same $2^{o} \times 5^{o}$ bins used by JEDA. Four months (January, April, July, and October) are chosen to represent the seasons. The seasonal cycle of mixed layer deepening coinciding with the onset of winter storms in the middle and high latitudes, and the subsequent shallowing in summer is reproduced. The magnitude of the MLD (Figure 5) is slightly over-estimated in the tropics and is under-estimated outside of them. Errors are expected in the interpolated data product resulting from the spatial distribution of the XBTs, however it appears that some aspects of the mixed layer formulation that need to be reconsidered. Finally, the position of the North wall of the Gulf Stream was compared with current meter data. The separation point of the Gulf Stream is seen to be in the right place but the deflection angle is too far to the south.

Future Global 0.1 ^{o} POP Simulation

These results were presented at a workshop attended by Navy and university researchers involved in the development of the global coupled prediction system that was held in December 1999. Recommendations were made that the horizontal resolution for the ocean component should be 0.1 ^{o}. In the light of our results and their recommendations it was decided that the global ocean component should be run at this horizontal resolution with 40 vertical levels. Such a simulation will require far more resources than originally requested. Benchmarks on the Army Research Laboratory Origin2000 show that 45 cpu days are required to produce 1 model year at this resolution. Since the code is highly scaleable, we would expect this estimate to be halved on the 256 processor SN1. A twenty-year run would need roughly 3 million processor hours (540 CPU hours x 256 processors x 20 years). As before we are planning to spin-up for roughly two decades and then run for 5-7 years using prescribed surface forcing from the Navy Operational Global Atmospheric Prediction System (NOGAPS). We are currently preparing the topography (all channels have to be carefully checked to ensure proper flow) and the forcing fields, and anticipate starting this run in summer. Progress will be slow until we have access to the SN1 or other architecture with a sufficient number of processors. It should be noted that output from this model run will be supplied to FNMOC at various times over the 2-decade spin-up. FNMOC has officially decided to use POP and these fields will be used for testing in their forecasting algorithms.

PIPS 3.0 progress to date

A newly configured 1/12 ^{o} (~9 km) and 45 level coupled ice-ocean model of the Pan-Arctic region has been already integrated for almost a decade during the first year of the Grand Challenge allocation (http://www.oc.nps.navy.mil/~pips3/). The model is forced with1 day-averaged climatological atmospheric fields derived from 1979-1993 European Centre for Medium-range Weather Forecasts (ECMFW) reanalyzed data. It requires ~30 minutes per day and ~8 days to complete 1 year of model simulation using 128 T3E-900 nodes at the Arctic Region Supercomputing Center. In this phase of analysis and evaluation of model improvements a year of model output requires ~ 100GB disk space. This project is an extension of our earlier modeling study of the Arctic Ocean and sea ice (Maslowski et el., 1999, Zhang et al., 1999) at somewhat lower resolution (~18 km and 30 levels) and over a smaller domain. The PIPS 3.0 model domain extends from the North Pacific at ~30 ^{o} N through the Arctic Ocean into the North Atlantic to ~40 ^{o} N. It includes the Sea of Japan, Sea of Okhotsk and the Bering Sea on the Pacific side and the Barents, Nordic, Labrador, Irminger, North and Baltic seas on the Atlantic side. This is also to our knowledge the first model realistically representing the Canadian Archipelago, one of the two main exits of fresh water from the Arctic into the Atlantic Ocean. The model domain array size is (1280x720x45), which computationally is ~24 times bigger than our earlier problem. Its horizontal grid spacing is not yet fully eddy resolving in the Arctic Ocean, where the first baroclinic Rossby radius (determining the size of eddies) ranges between 10 and 50 km. In order to satisfy this condition a basin-wide grid cell size of 2-3 km is required what computationally remains a problem of future Grand-Challenge proportions. At the same time by employing a high resolution both in horizontal and vertical directions this model addresses some of the main environmental focus areas of the DON Science and Technology.

The model allows studies of small to large scale processes with special emphasis on the shelf and littoral regions, as it provides exceptionally high vertical resolution in the upper ocean (17 levels between 0 and 300 m). Not only the vast arctic shelves but also deep basins, submarine ridges, straits and narrow channels are represented at the highest possible detail. This is in part a result of use of free-surface approach and of incorporation in the model of state-of-the-art bathymetry data recently compiled by the International Bathymetric Chart of the Arctic Ocean (IBCAO) group (Jakobsson et al., 2000). The Arctic Ocean circulation is strongly barotropic, which means that its major portion is influenced by bottom relief changes, especially in shallow and high depth gradient (e.g. continental slope) areas. Ocean currents in turn have a strong effect on sea ice thickness, concentration and ice edge position. For example, the continuous recirculation of the warm Atlantic Water in the Greenland Sea determines the ice edge position along the shelf slope of Greenland. Compared to other seas there is very little seasonal variability in the east-west sea ice extent over this region. This is demonstrated in Figures 6 and 7, where seasonal variability of sea ice extent and associated surface temperature and currents in the Greenland Sea are shown. In contrast the ice extent on the Pacific side of the model in the Bering/Chukchi Sea varies dramatically within a year. The ice edge position is defined along the continental slope of the Bering Sea in winter and it moves by more than 1000 miles north into the Chukchi Sea in summer (Figures 8) and it is strongly influenced by the ocean surface temperature and velocity fields (Figure 9). Knowledge of all these parameters (i.e. ice edge position, thickness and concentration, upper ocean currents and stratification) is critical to successful naval operations in the ice-covered environment.

This project will also significantly contribute to integrated analysis and synthesis of a number of ongoing or recently completed ONR-sponsored field projects (e.g. SCIECEX, SHEBA, Western Arctic Shelf Basin Interactions, Japan/East Sea Program, Labrador Sea Convection Project, New Water Polynya and North Water Polynya projects and Arctic Nuclear Waste Assessment Program). Results from a high resolution model provide a unique opportunity to integrate information regarding the spatial and temporal variability of local processes with the large scale dynamics of the region. Such information is never available at sufficient level from observations. In addition such high resolution models with increasingly realistic representation of ice and ocean environments should prove very useful in guiding future field experiments of high relevance to the U.S. Navy.

Outstanding Tasks

During the spin up the coupled model uses our earlier parallel version of the thermodynamic-dynamic sea ice model of Hibler (1979), including the zero-layer thermodynamics (Semtner, 1976), the surface heat budget (Parkinson and Washington, 1979) and a viscous-plastic rheology. The new sea ice model currently being adapted into the PIPS 3.0 follows the approach of Bitz et al. (2000). Some of the major improvements include: multi-category ice thickness distribution, multiple ice layers to resolve non-linear vertical ice temperature and salinity profiles, a snow layer, a brine pocket parameterization and assimilation of ice motion and satellite derived ice concentration data while in operational mode. Initial evaluations of these modifications are very encouraging. We are confident that this new sea ice model will significantly improve representation of important processes controlling sea ice dynamics and thermodynamics. Combination of physics improvements and high resolution will allow to address such important issues as lead orientation, ice thickness distribution, ridging, divergence and ice edge position, their statistics and temporal and spatial variability. In addition, we will replace the ocean code with its newer version, which includes mixed layer (KPP, Large et al., 1994) and isopycnal mixing (GM, Gent and McWilliams, 1990) parameterizations. The operational model will use a distributed shared memory (DSM) platform, such as the SGI Origin 2000 currently available at FNMOC. During the second year of the Grand Challenge allocation we will continue the model spin up on the T3E at ARSC and in parallel will port and optimize the coupled model on the Origin 2000 at ARL. The atmospheric fields from the NOGAPS model will be used to evaluate PIPS 3.0 forecasts under operational atmospheric forcing.

Conclusions

Evaluations of a 0.1^{o}, 40-level and a 0.28^{o}, 20-level POP run in the North Atlantic using high frequency data show that model fidelity increases significantly at the higher resolution. It is demonstrated that the coarser resolution inadequately reproduces the mean and variability of the surface circulation. Consequently, it is recommended that a global 0.1^{o}, 40-level POP simulation be performed in place of the originally proposed coarser simulation. Comparison of the regional Pan-Arctic coupled model at 1/12^{o} and 45 levels with its earlier, lower resolution version at 1/6^{o} and 30 levels indicates about fourfold increase of the mean total kinetic energy in the system. This increase is mainly due to enhanced eddy resolution. In addition, the higher resolution model allows to properly resolve the large scale but narrow (~100 km) boundary currents, which are the dominant feature of the Arctic Ocean circulation. The high resolution in sea ice approaches an aggregate scale, which can be reasonably well represented by sub-grid process parameterizations.

Acknowledgments

The Office of Naval Research and the National Science Foundation provides funding for these projects. The Arctic and North Atlantic model simulations were performed at Department of Defense High Performance Computing Centers in Alaska (Arctic Region Supercomputing Center) and Maryland (Army Research Laboratory). We thank the staff at both these sites for their technical support. The 0.28° POP simulation was performed at the Advanced Computer Laboratory at the Los Alamos National Laboratory. The Atlantic Oceanographic and Meteorological Laboratory Drifting Buoy Data Assembly Center provided the drifter data and the Joint Environmental Data Analysis Center provided the mixed layer depth product. Pam Posey (NRL, Stennis Space Center) supplied the archived NOGAPS wind stresses. Mathew Maltrud (LANL), Jimmy Pelton (NPS) and Pierre Poulain (NPS) are collaborators on the North Atlantic/global project.

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Figures

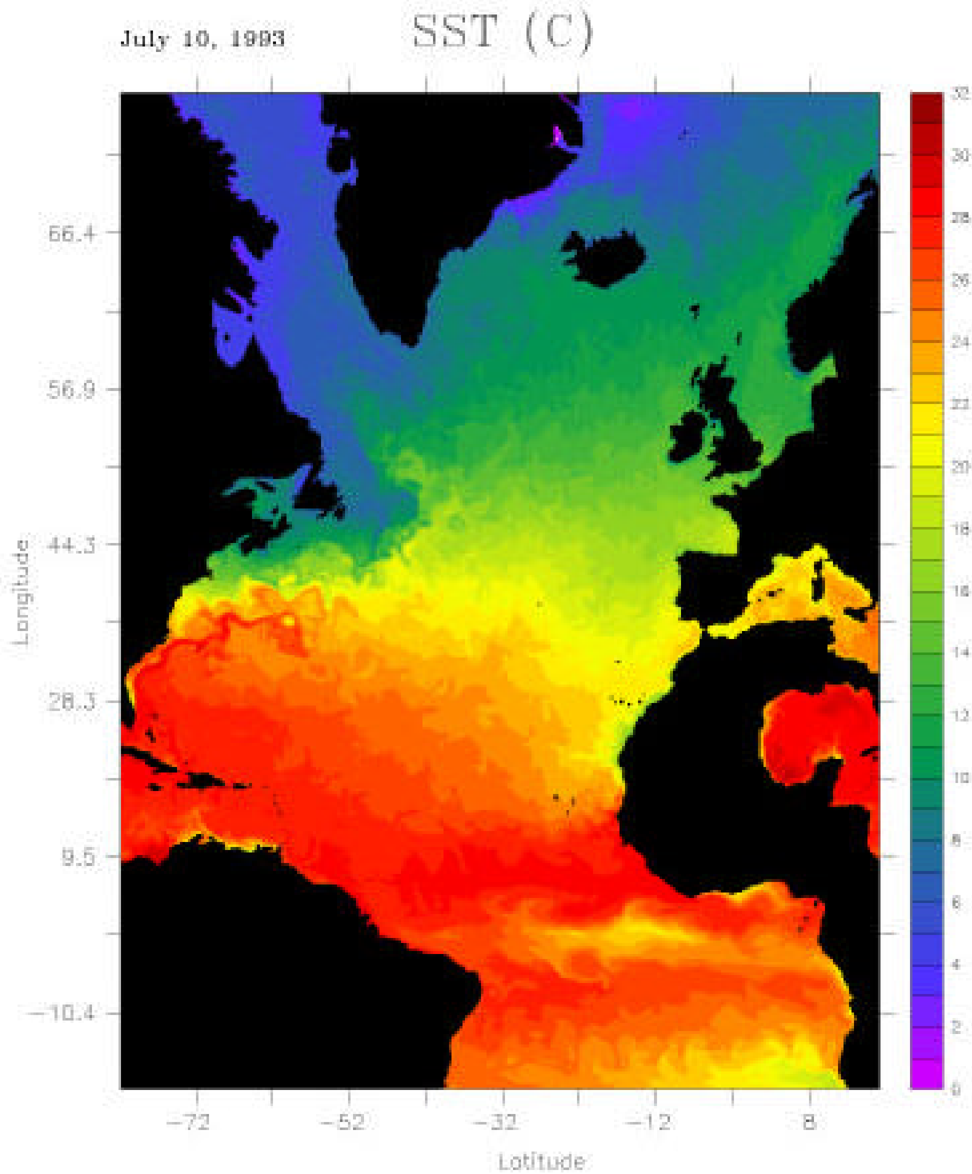


Figure 1: Snapshot of temperature (°C) in the uppermost model level (5 m) from the North Atlantic 0.1^{o} POP simulation.

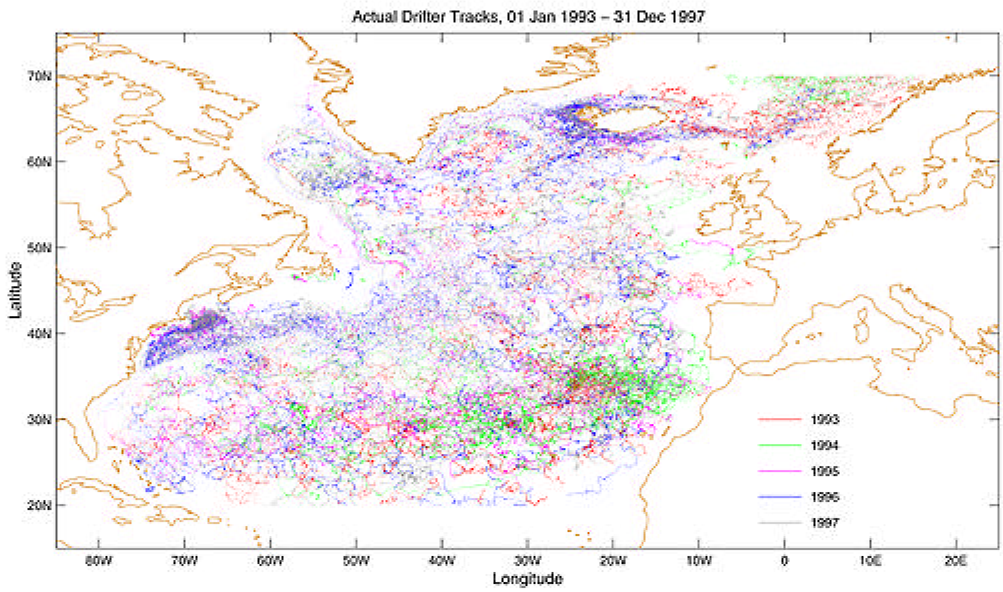
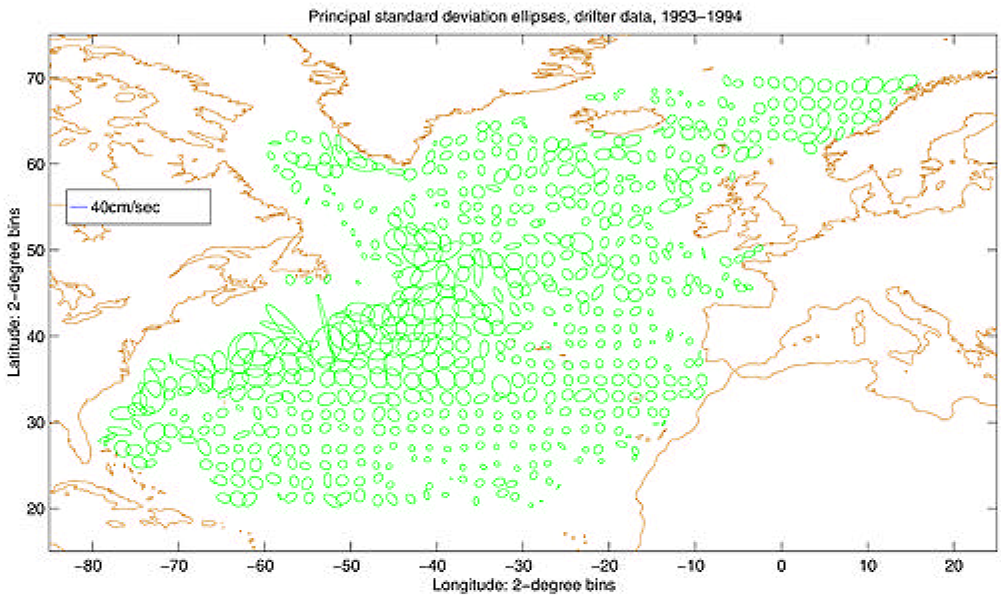
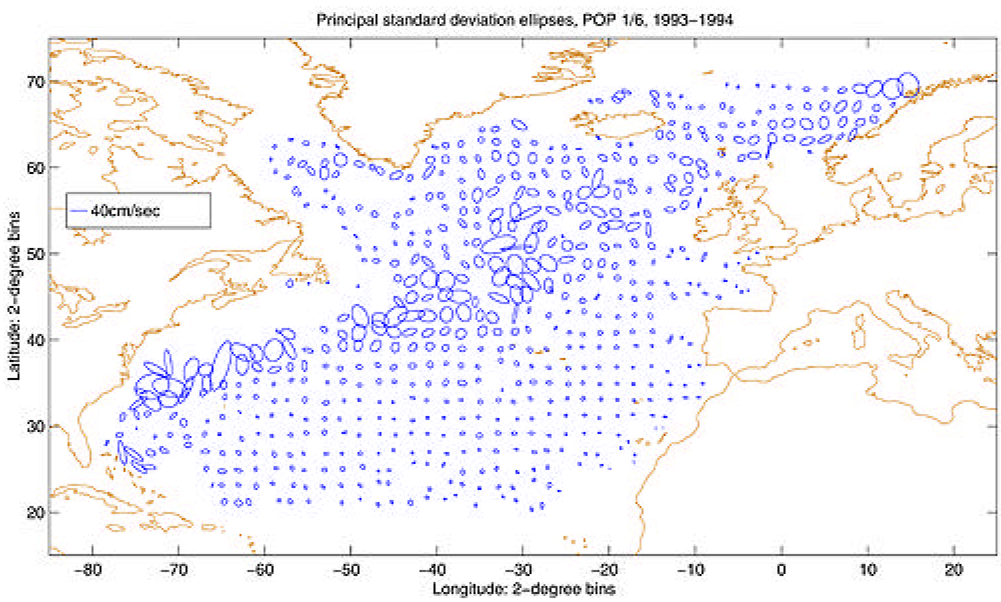


Figure 2: Trajectories of North Atlantic World Ocean Circulation Experiment surface drifters for the years 1993-1997.



(A)



(B)

Figure 3: Principal standard deviation ellipses for the (a) drifters, (b) the 0.1^{o}, and (c) 0.28^{o} POP runs.

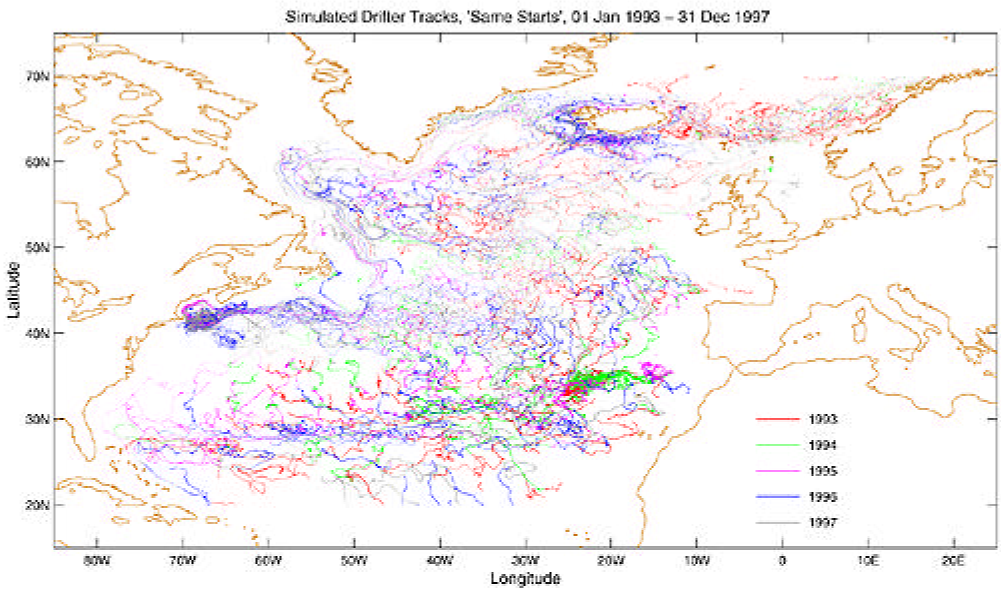


Figure 4: Numerical trajectories from 0.28^{o} POP in the North Atlantic.

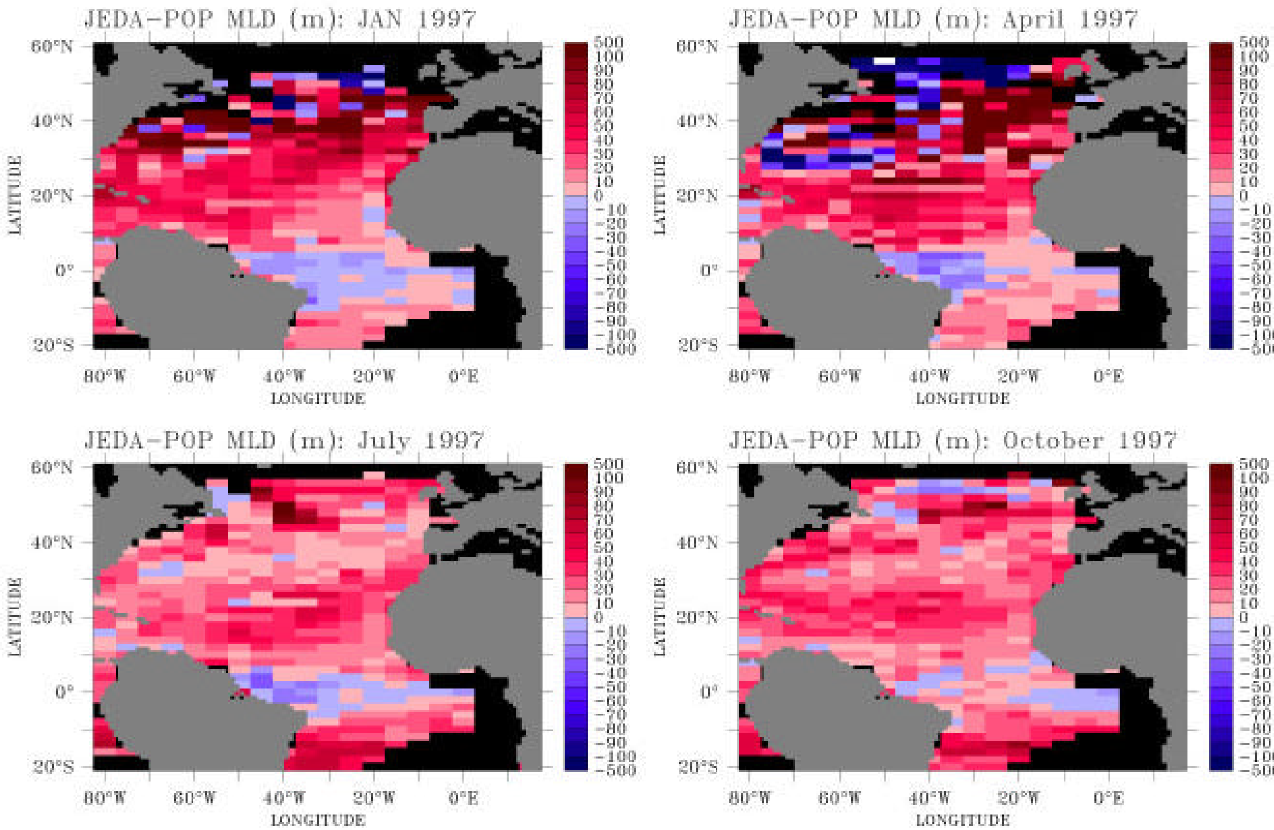


Figure 5: Differences between simulated and observed mixed layer depths for the months of January, April, July and October, 1997. The observations are based on XBTs and the model quantities are derived from the 0.1 ^{o} North Atlantic POP run.

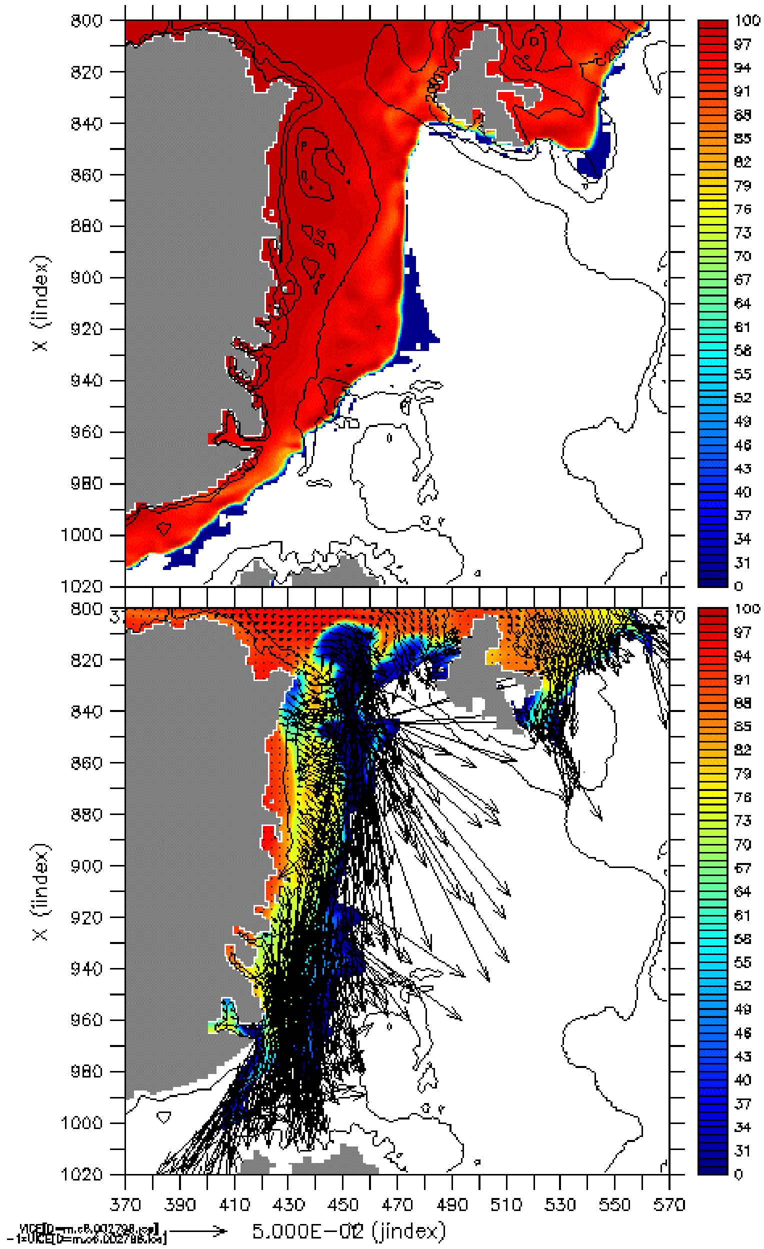


Figure 6. Sea ice concentration (%) and velocity (m/s) in the Nordic Seas from the PIPS 3.0 in (top) March and (bottom) August after 8-year spinup. Unit vector represents 0.05 m/s.

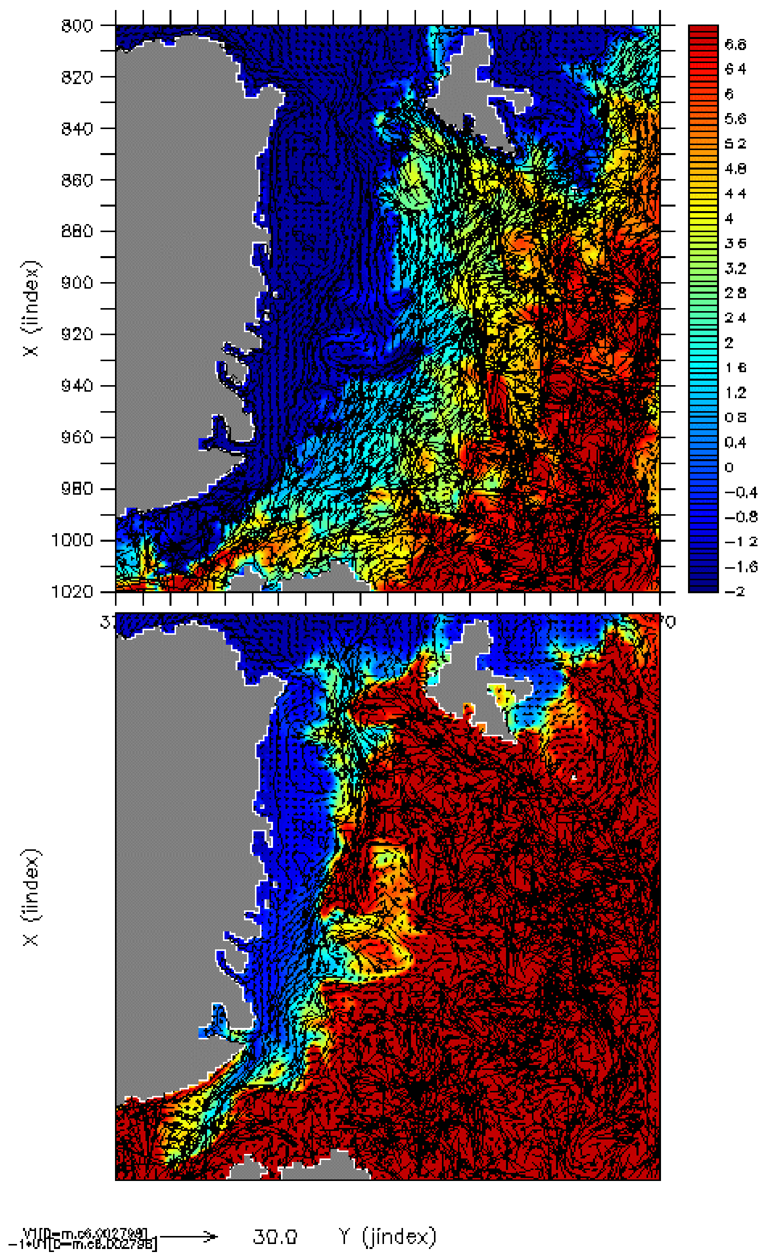


Figure 7. Surface (0-5m) temperature (^{o} C) and velocity (cm/s) in the Nordic Seas from the PIPS 3.0 in (top) March and (bottom) August after 8-year spinup. Unit vector represents 30 cm/s.

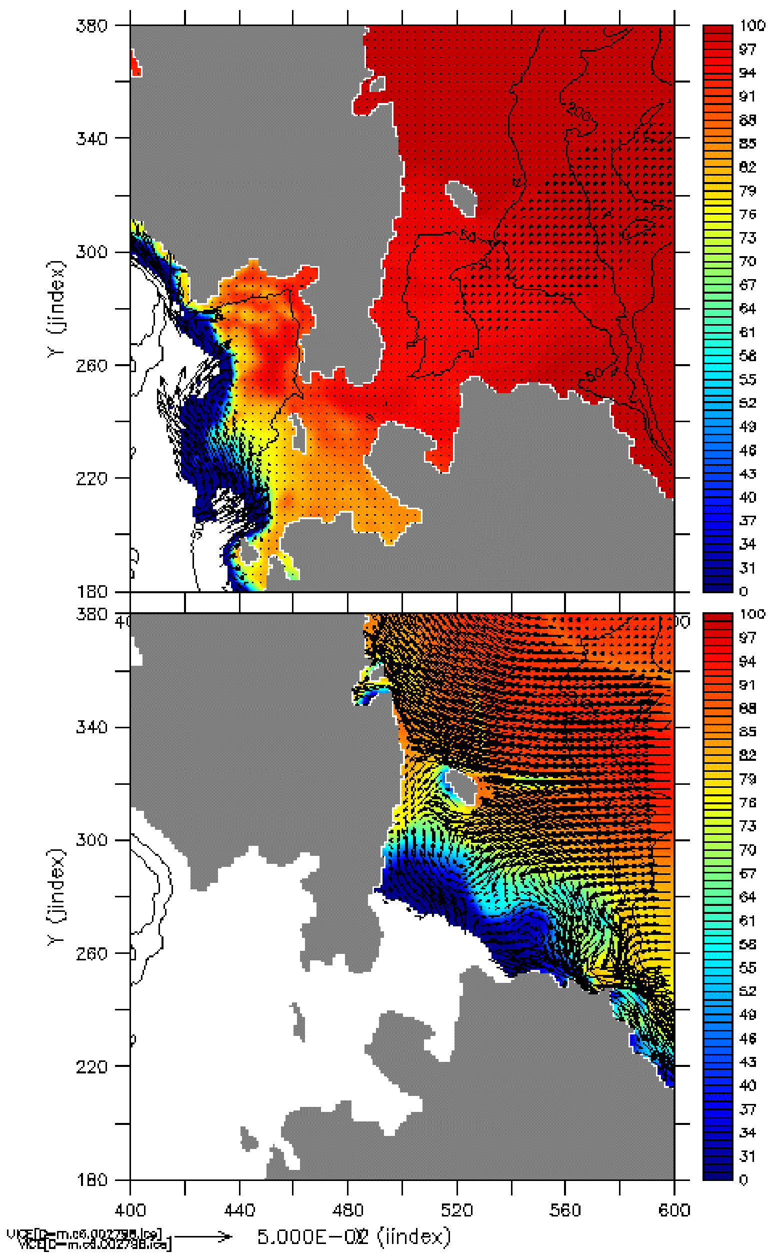


Figure 8. Sea ice concentration (%) and velocity (m/s) in the Bering/Chukchi Sea from the PIPS 3.0 in (top) March and (bottom) August after 8-year spinup. Unit vector represents 0.05m/s.

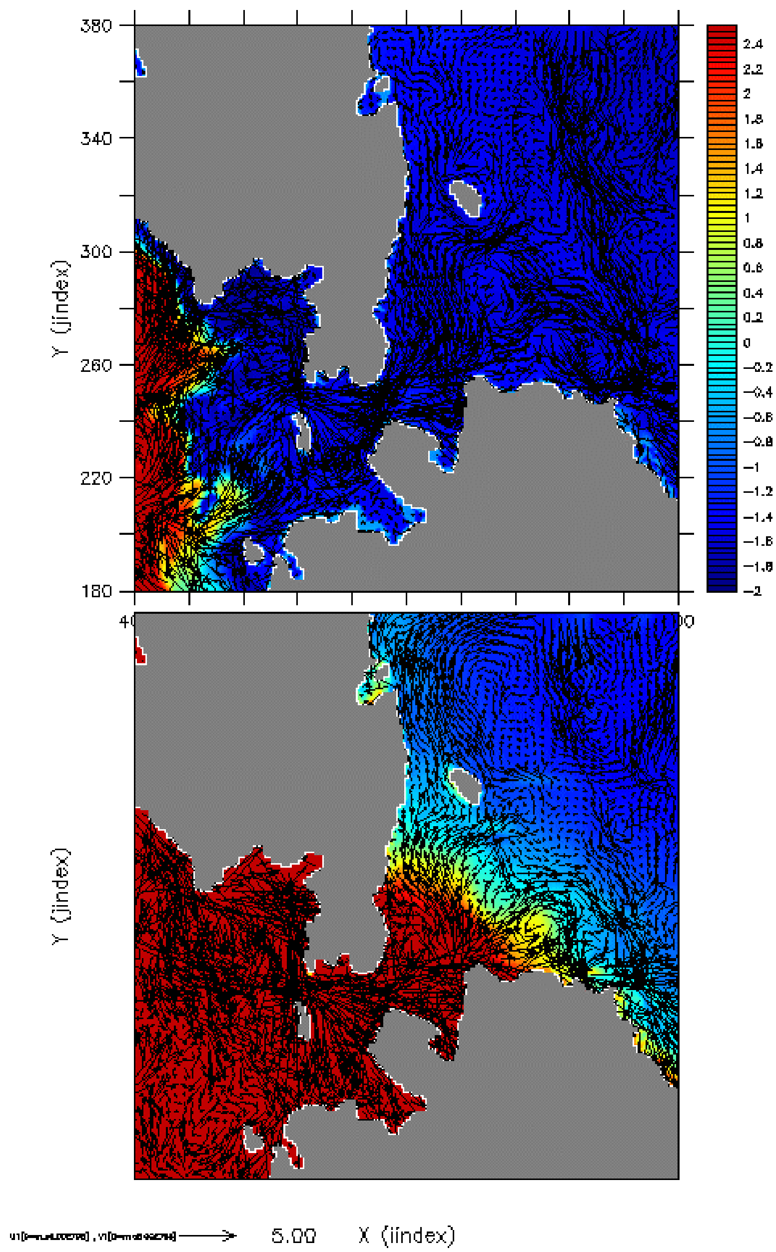


Figure 9. Surface (0-5m) temperature (^{o} C) and velocity (cm/s) in the Bering/Chukchi Sea from the PIPS 3.0 in (top) March and (bottom) August after 8-year spinup. Unit vector represents 5 cm/s.